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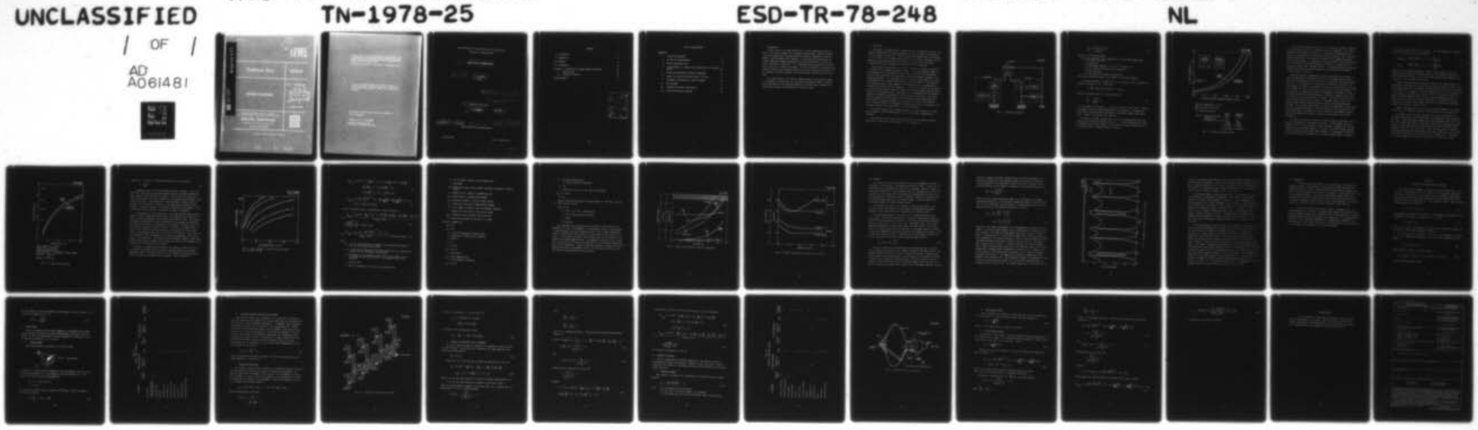

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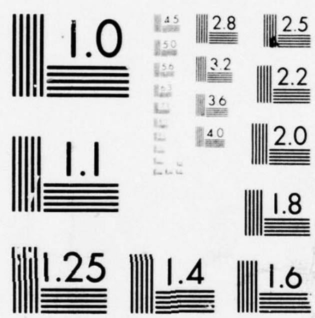

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Technical Note 1978-25

Satellite Crosslinks

W. C. Cummings

4 August 1978

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FOR THE COMMANDER

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(6) # SATELLITE CROSSLINKS,

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I. INTRODUCTION

A brief study of the characteristics of a 60 GHz crosslink has been conducted. The study considers the incremental launch weight tradeoffs between a link using mechanically steerable parabolic reflector antennas and electronically steerable phased array antennas. An algorithm which determines the optimum compromise between transmitter power and aperture size for these two types of antennas is developed. It is concluded that the phased array antenna can be used only for small scan angles. With this restriction, the phased array antenna provides a better weight compromise for data rates below 100 kbps while the parabolic reflector antennas are to be preferred for data rates above 100 kbps.

The susceptibility of the link to jamming attack is also briefly studied. It is generally concluded that the link will be relatively immune to jamming attack provided that the autotrack function of the link and the communication function both operate over bandwidths of 100 KHz or more.

II. DISCUSSION

We consider a communications crosslink between two satellites in orbit. The satellite orbits need not be geosynchronous although throughout the discussion this is assumed to be the case. The discussion also assumes that the satellites are in the same or very similar orbits such that they remain relatively fixed in relation to each other and that the satellites are three-axis stabilized. Crosslink communication between two satellites only is considered.

Each of the two satellites in the link is assumed to contain a transmitter, a receiver, and an antenna as shown in Figure 1. The communications signal to be transmitted from one satellite to the other is applied to the transmitter which, using a mixer and local oscillator, converts the signal frequency to the crosslink frequency. The converted signal is then amplified either by a single power amplifier or a group of amplifiers which combine outputs. The amplified and converted signal is then applied to the antenna through a diplexer which isolates the receiver from the transmitter. Two types of antenna are considered; an on-focus fed parabolic reflector antenna and an electronically steered phased array of electromagnetic horns. Beam-steering is accomplished for the parabolic antenna by mechanically pointing it in the appropriate direction. The phased array is steered by electronically controlled phase shifters behind each horn. Both types of antennas are assumed to use sequential lobing in an autotrack mode. Antenna pointing is controlled by ground command, and the acquisition and tracking functions are controlled by the tracking receiver.

The received signal, with lobing modulation, is down converted in a mixer and is applied to the tracking receiver and to the on-board communications processor.

The efficiency of the link can be characterized by the signal-to-thermal noise ratio at the input to the receiver. This is given by

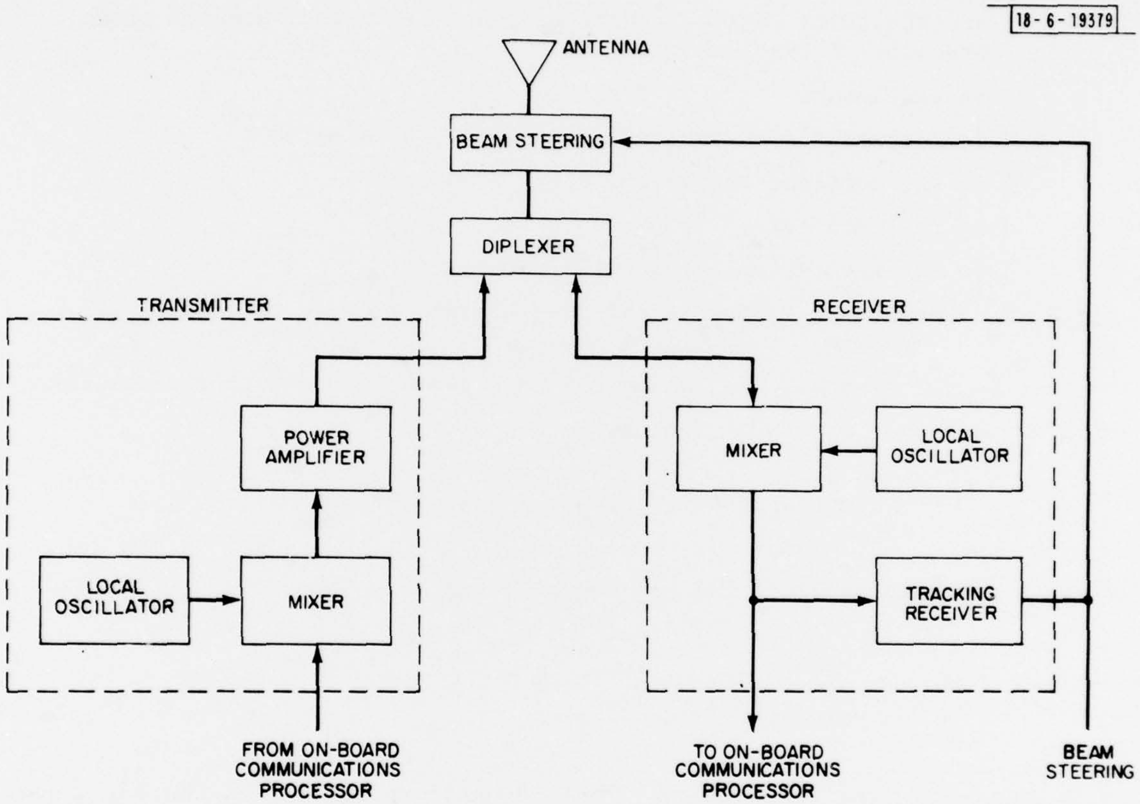


Fig. 1. Crosslink components.

$$\frac{E_b}{N_o} = \frac{K_T\, K_R\, P_T\, G_T\, G_R\, \lambda^2}{KTR(4\pi S)^2} \tag{1}$$

where P_T is transmitter power

G_T, G_R are the gains of the transmitting and receiving antennas along the line of the link

λ is wavelength

K is Boltzmann's Constant = 1.38×10^{-23} watts/Hz - °K

T is the receiver equivalent noise temperature

R is the data rate

S is the separation between the satellites

and K_T, K_R account for losses in the transmit and receive networks.

It seems reasonable to assume that the two antennas in the crosslink are similar such that $G_R = G_T$. Noting that

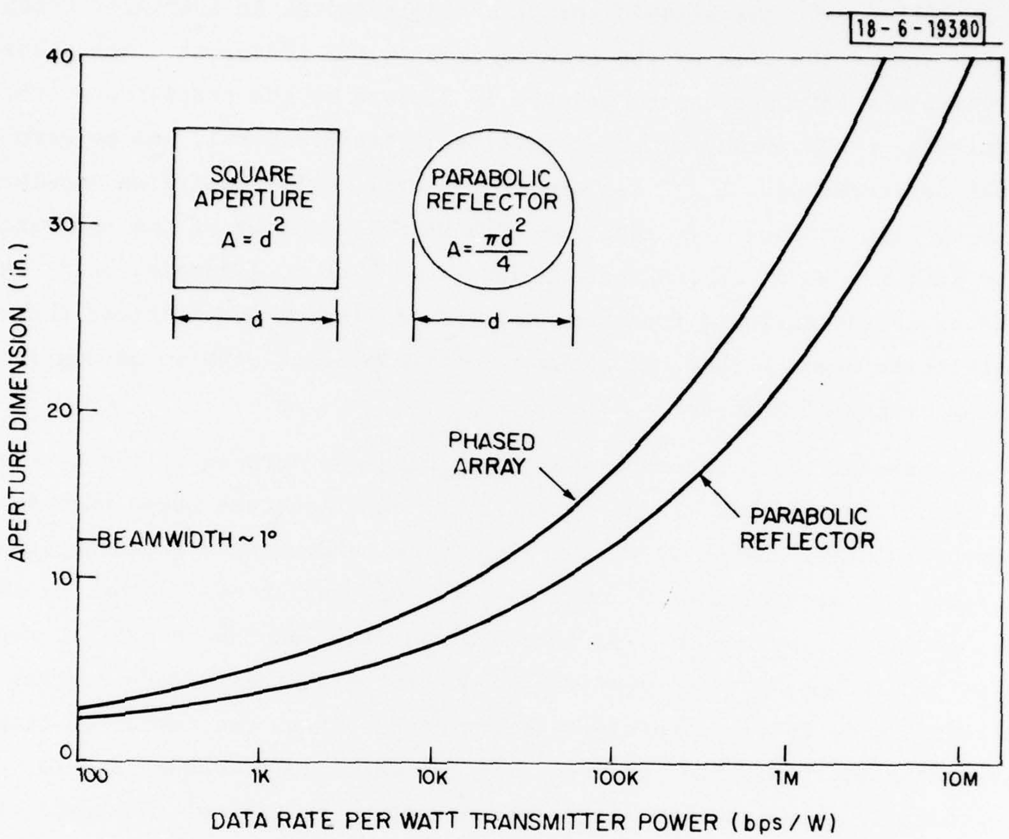
$$G = \frac{4\pi A}{\lambda^2} \times \text{aperture efficiency} \times \text{scan loss}$$

where A is aperture area, (1) can be rewritten as

$$\frac{E_b}{N_o} = \eta\, \frac{P_T A^2}{KTRS^2\, \lambda^2}\quad . \tag{2}$$

η is the total link efficiency. $\eta = K_T K_R(\text{aperture eff} \times \text{scan loss})^2$. Equation (2) suggests that the antenna dominates the link equation. The signal-to-noise ratio varies with the linear aperture dimensions raised to the fourth power. Figure 2 illustrates this dominance.

Note that at 60 GHz, moderate data rates can be realized with low transmitter powers and modest aperture sizes, i.e., a 9-inch aperture with one watt of transmitter power will support a 10 kbps data rate with a phased array or a 30 kbps rate with a parabolic reflector antenna.



RECEIVER TEMPERATURE = 1500 °K

$\frac{E_b}{N_o}$ = 6.92 (BER = 10^{-4} – QPSK)

S = 40,000 STATUTE MILES

		ARRAY	PARABOLA
LOSSES:	APERTURE EFFICIENCY	= −0.9 dB	−2.6 dB
	SCANNING LOSS	= −3.0	0
	TRANSMISSION LINE LOSS	= −2.5	−2.5
		−6.4 dB	−5.1 dB
	×2	−12.8 dB	−10.2 dB
		→ 0.052 net eff	→ 0.095 net eff

Fig. 2. 60 GHz link characteristic.

It will now be established that the time required to initially establish the link limits the size of the antenna used in the crosslink. The accuracy with which the antennas can be pointed is limited by the precision of the orbital fit, the accuracy of the satellite attitude control, and by structural thermal deformations. These factors, in general, will require an angular search by each antenna. In addition, the relative motion of the two satellites due to differences in orbital parameters gives rise to a doppler shift in frequency necessitating a frequency search. Following acquisition, these same instabilities require that the antennas maintain track with an automatic tracking system of some sort.

Acquisition may be accomplished by holding one antenna in the link at a fixed pointing angle and frequency while the other antenna steps through a series of pointing angles in a search pattern, conducting a frequency search at each step. If acquisition is not made after completion of this cycle, the first antenna is pointed in a different direction, and the process is repeated. This procedure has been successfully demonstrated in the LES-8/9 program. The time required to complete this process is dependent on the number of steps in the search pattern and the time required to search in frequency and to shift the antenna from one pointing angle to another. The size of the steps of the search pattern should be on the order of a beamwidth, and the size of the angular window searched should be several times the pointing uncertainty. Similarly, the frequency search should be made over a band several times larger than the frequency uncertainty. The time required to shift the antenna from one pointing angle to another will be much longer for the parabolic antenna than for the phased array since the parabolic antenna must be physically re-oriented.

In order to illustrate the effect of aperture size on acquisition time, we choose the parameters of the LES-8/9 crosslink. In this system, the search window is 2.1 x 3.5°, the frequency search requires 2.3 seconds, and the time required to shift pointing angles is .5 second. Since LES-8/9 uses a mechanically steered antenna, we apply these parameters to the parabolic reflector. The time required for the phased array to shift pointing angles is assumed to

be less by a factor of ten, or .05 second. The times required to completely perform the search cycle are then given by

$$T_{parabola} = \left(\frac{2.1}{BW}\right)^2 \left(\frac{3.5}{BW}\right)^2 (2.3 + .5) = \frac{151.3}{(BW)^4} \text{ sec} \tag{3}$$

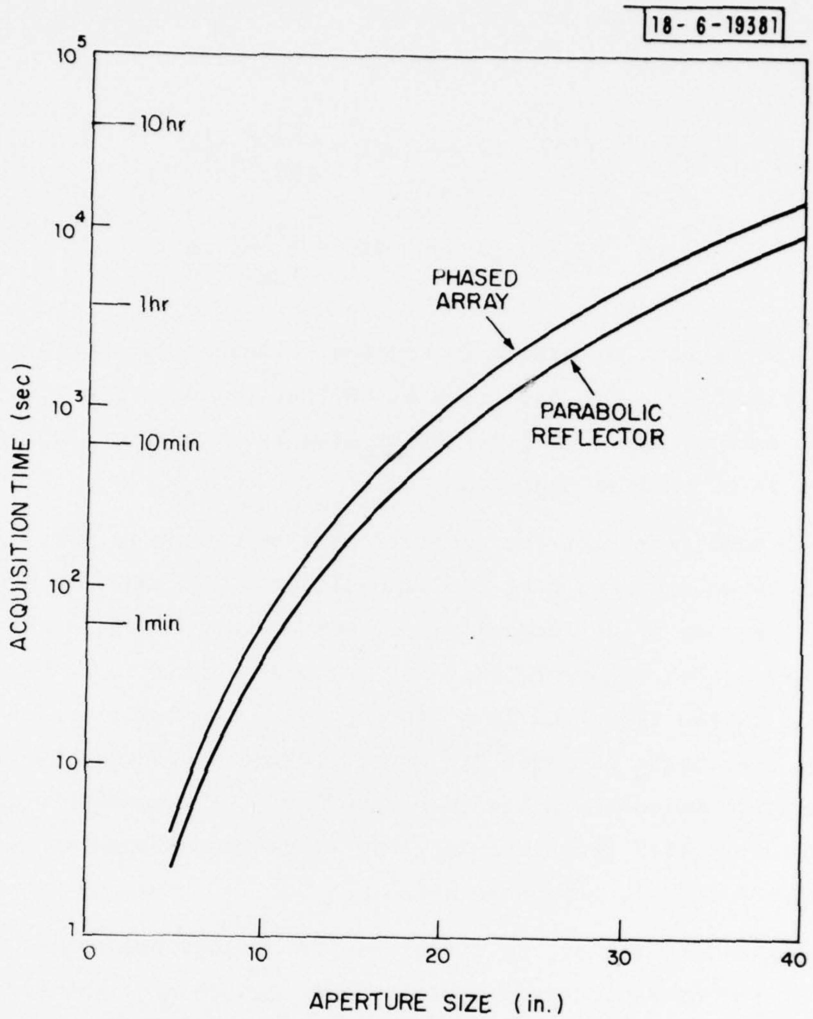
$$T_{array} = \left(\frac{2.1}{BW}\right)^2 \left(\frac{3.5}{BW}\right)^2 (2.3 + .05) = \frac{127.0}{(BW)^4} \text{ sec} \tag{4}$$

where BW is the antenna beamwidth in degrees. These times are plotted vs. aperture size in Figure 3. Note that at 60 GHz, the aperture size must be of the order of thirty inches or less if the time required for a complete acquisition cycle is to be less than one hour.

Figure 2 indicates that the parabolic reflector can support higher data rates with a given aperture size and transmitter power than can a phased array. This results because of the scanning loss experienced by the array in pointing a beam off axis. For Figure 2, this was assumed to be 3 dB. The scanning loss is the result of the reduction in pattern gain of the individual horns in the array as the scan angle is moved off axis. Figure 2 assumes the array scan angle off axis to be one half the horn beamwidth. The parabolic reflector antenna does not suffer from scanning loss since the antenna is mechanically steered, and the beam is always on axis.

Figure 3 indicates that, by virtue of its broader beamwidth, the acquisition time for the parabolic reflector is less than that of the phased array.

The angular sector over which the array can scan is determined by the acceptable scanning loss and the beamwidth of the individual horns comprising the array. Large scan angles require large horn beamwidths, hence small horns. Thus, for a given array size, a capability to scan over a large angle requires an array of many small horns while the capability to scan over small angles requires an array of a few large horns. Thus, the array which is capable of scanning large angular sectors requires more phase shifters and a more complex feed network than does the array which can scan a small sector. The number, N, of horns required in an array of aperture size, d, with a scan angle



SEARCH WINDOW — 2.1° × 3.5°
SEARCH STEP — 1 BEAMWIDTH
FREQUENCY SEARCH — 2.3 sec
TRANSITION TIME — 0.5 sec PARABOLA, 0.05 sec ARRAY
ARRAY BW — $\frac{60\lambda}{d}$ deg
PARABOLA — $\frac{70\lambda}{d}$ deg

Fig. 3. 60 GHz acquisition time.

capability, α, and with a maximum scanning loss of 3 dB is given by

$$N \simeq \left(\frac{d\alpha}{60\lambda}\right)^2 \tag{5}$$

A parametric plot of this relationship is shown in Figure 4. This suggests that crosslinks which utilize phased arrays will confine themselves to small aperture sizes and small scan angles. The fact that the scan angle is small means that the satellites involved in the crosslink must maintain a fixed orbital separation. The mechanically steered parabolic reflector does not encounter this limitation, although its scan angle may be limited by other factors. In general, however, the parabolic reflector can be designed to scan large angular sectors without a concomitant increase in complexity.

A consideration of prime importance in any space platform system design is weight. Technical approaches which appear to be superior can be ruled out in favor of inferior approaches simply because they weigh too much. The weight of a spaceborne communications link is determined by the weights of the antenna, the antenna feed system, the transmitter, the receiver, the power supply, and the structural supports required for these. In addition, the weight added by these factors requires increased capability, hence weight, in the attitude control, stationkeeping and telemetry systems of the satellite. What counts is the incremental weight engendered by the communications package in the launch weight of the spacecraft. Algorithms have been developed, based on weight data from previous satellite designs, which reflect the weight of the communications package into the incremental launch weight.

Generally, a communications link which will support a given data rate can be designed for minimum weight by properly balancing aperture size against transmitter power. The optimum weights for the phased array and the parabolic reflector antenna are developed in the appendix. These are given by

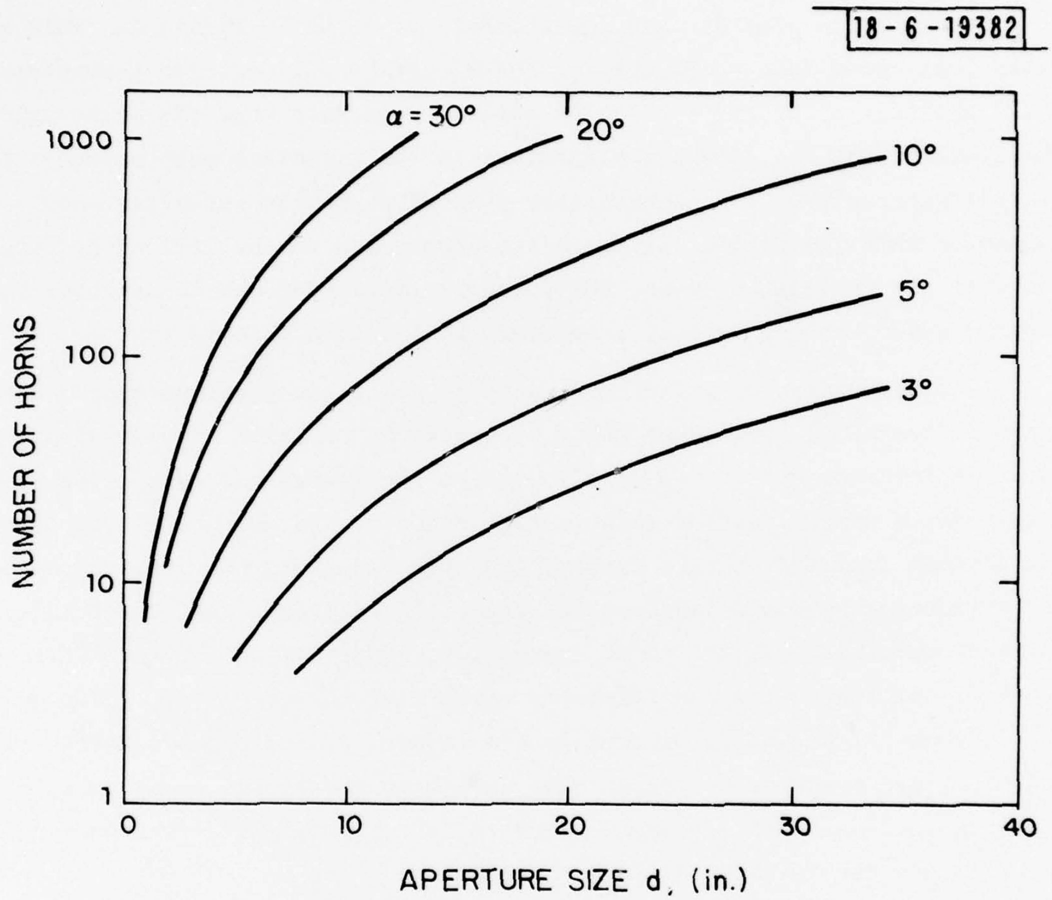


Fig. 4. Array elements vs aperture with scan angle as a parameter 60 GHz.

$$\Delta W_{L_{min}} \simeq K_1\{6\delta\, d^2 t + \frac{3}{2}\left(\frac{d\alpha}{60\lambda}\right)^2 (w_p + \sigma) + \frac{\sigma}{12}\left[\frac{d\alpha}{60\lambda}\left(10 + 6\log_2 \frac{d\alpha}{60\lambda}\right)\right.$$

$$\left. + \frac{d}{\ln 2}\left(\frac{d\alpha}{60\lambda} + 1\right) + 5d \log_2 \frac{d\alpha}{60\lambda}\right] + W_o\} \quad (6)$$

$$+ K_2\left[\frac{3}{2}\left(\frac{\alpha d}{60\lambda}\right)^2 p_\phi + P_o\right] \text{ - Phased Array}$$

$$\Delta W_{L_{min}} \simeq K_1\{\delta \frac{\pi d^2}{4}\left[\left(\frac{K^2+1}{K}\right)^{3/2} - K^2\right] + \frac{15\gamma d}{16}\sqrt{\frac{8K-1}{K^2}} + \frac{5\sigma d}{16}\left(\sqrt{\frac{8K-1}{K^2}} + 2\right) + W_o\}$$

$$+ K_2 P_o \text{ - Reflector Antenna} \quad (7)$$

and the transmitter powers corresponding to these are given by

$$P_T \simeq \frac{\Delta W_{L_{min}} + K_1\left[4\delta d^2 t + \left(\frac{d\alpha}{60\lambda}\right)^2 (w_p + \sigma) + \frac{\sigma d}{2}\left(\frac{d\alpha}{60\lambda}\log_2\left(\frac{d\alpha}{60\lambda}\right) + \frac{1}{\ln 2}\left(\frac{d\alpha}{60\lambda}\right) + \frac{1}{\ln 2}\right) - W_o\right]}{5(K_1 w_{pa} + K_2\beta)}$$

$$+ \frac{K_2\left[\left(\frac{d\alpha}{60\lambda}\right)^2 - P_o\right]}{5(K_1 w_{pa} + K_2\beta)} \text{ - Phased Array} \quad (8)$$

$$P_T \simeq \frac{\Delta W_{L_{min}} - K_1 W_o + K_1\delta\, \frac{\pi d^2}{6}\left[\left(\frac{K^2+1}{K}\right)^{3/2} - K^2\right] - K_2 P_o}{5(K_1 w_{pa} + K_2\beta)} \text{ - Reflector Antenna} \quad (9)$$

where

K_1 = a factor which reflects the weight of the communications package into the incremental launch weight

K_2 = a factor which reflects the buss power required by the communications package into the incremental launch weight

δ = the density of the material (lb/in^3) used in the phased array or the weight per unit area (lb/in^2) of the material used in the reflector

d = aperture size

t = the wall thickness of the horns in the phased array

α = the scan angle required for the phased array

λ = wavelength

w_p = phased array phase shifter weight (ϕshifter + polarizer + ϕshifter driver)

σ = weight per unit length of transmission line

W_o = fixed weight of communications package

p_ϕ = buss power required to drive one phase shifter

P_o = fixed power required by communications package

K = focal length to diameter ratio for parabolic reflector

γ = weight per linear inch of feed support struts

w_{pa} = transmitter power amplifier pounds per watt

β = buss watts required for one watt of rf power

By way of example use:

K_1 = 1.7

K_2 = .85

δ = .1 lb/in^3 (aluminum for phased array)

= .0045 lb/in^2 (composite for reflector)

t = .062 in.

α = 5°

λ = .197 in

w_p = .28 lb.

σ = .0042 lb/in

W_o = 40 lb (phased array)

= 47 lb (parabolic reflector)

p_ϕ = .1 watt

P_o = 40 watts (phased array)

72.5 watts (parabolic reflector)

$K = .33$

$\gamma = .0034$ lb/in (.375 OD x .031 wall tube aluminum)

$w_{pa} = 3$ lb/watt

$\beta = 10$

Figure 5 shows the variation in optimum weight vs. data rate using (6), (7), (8), (9) and (2) with

$E_b/N_o = 6.92$

$\eta = (.81)^2 \; (.5)^2 \; (.46)$ phased array

$= (.55)^2 \; (.46)$ parabolic reflector

$T = 1500°K$

$S = 40{,}000$ mi

This indicates that the options are the same for a data rate in the vicinity of 10^5 bps. The beamwidth of the parabolic antenna is approximately .5° necessitating a 1/2 hour acquisition cycle. The rf power requirements, however, are quite low; on the order of 250 mw which is within today's technology. If the range is reduced, then the data rate can be increased by the square of the range reduction ratio. For example, at 13,000 mi ($\sim$30° separation) a data rate of 10^5 bps can be supported by a 9-inch square phased array and a 700 mw transmitter. Figure 6 shows the variation in weight for both the phased array using the parameters listed on the previous page with the data rate fixed and varying aperture size and power.

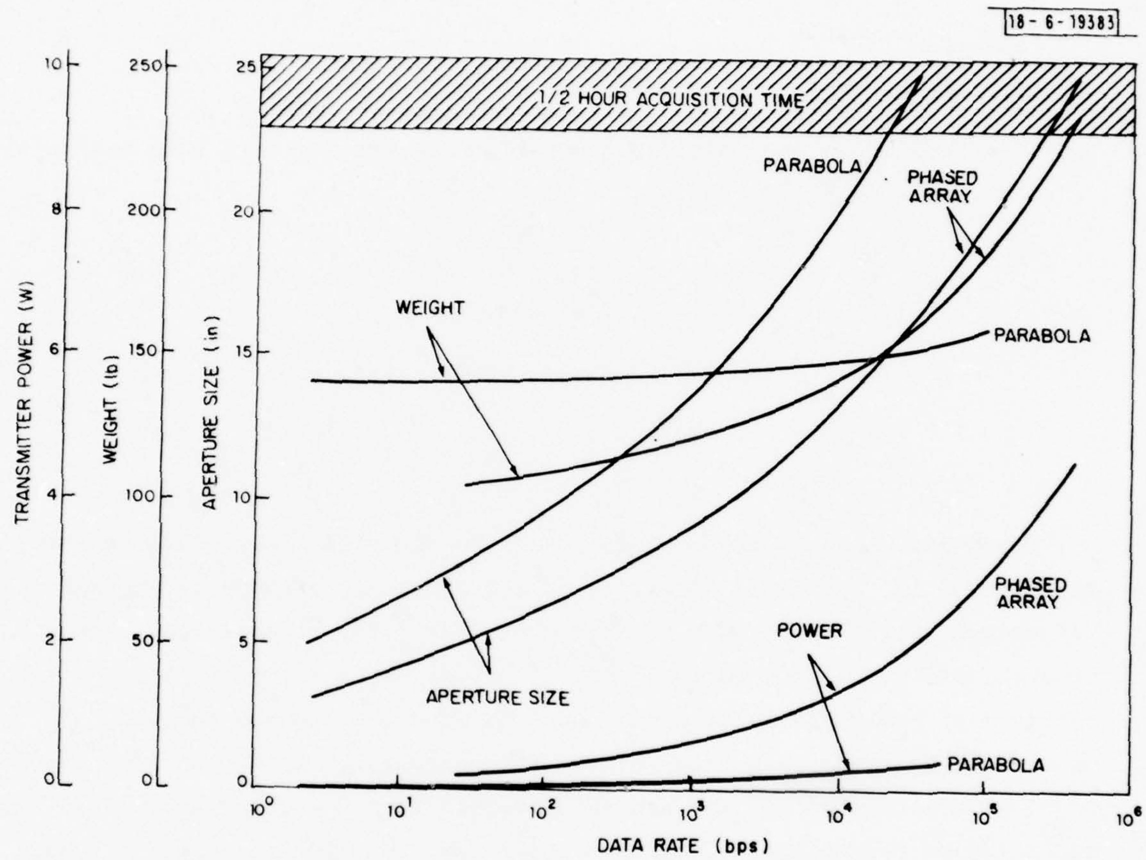


Fig. 5. Phased array/parabolic reflector comparison.

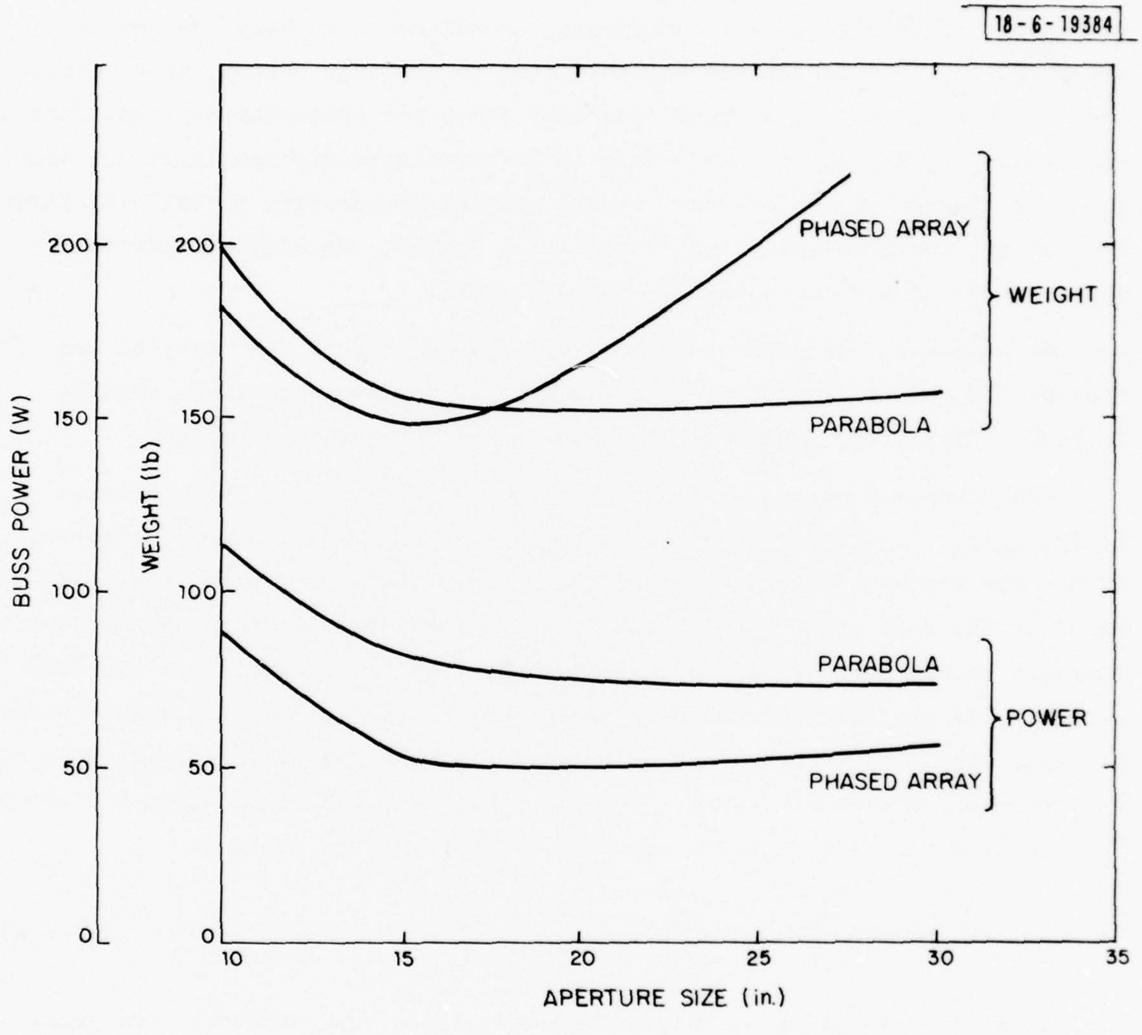


Fig. 6. Weight vs aperture size; data rate = 10^5 bps.

III. JAMMING

Up to this point, we have considered some of the parameters pertinent to the design of an effectively functioning crosslink at 60 GHz. We now turn our attention to the vulnerability of this link to jamming. Using, as a model, a link which functions at a fixed frequency (does not frequency hop) and does not possess any AJ attributes other than those which serendipitously result from the basic design of the system, we will attempt to quantify in ballpark terms some of the characteristics of a successful jammer. We will consider both earth-based jammers and satellite-based jammers.

An adversary can disrupt the crosslink in either of two ways; he can disrupt the autotrack system or he can disrupt the communications signal. Consider, first, the possibility of disrupting the autotrack system.

The crosslink maintains a data rate, R, at a minimum signal-to-noise ratio, E_b/N_o. The total received power is then RE_b, and the power received within the tracking receiver bandwidth, W, assuming a communications bandwidth equal to the data rate, is $W/R \times RE_b = WE_b$. The jammer, then, must be able to transmit enough power to approximately equal this power level. If the bandwidth, W, is smaller than the data bandwidth, R, the jammer need only transmit a signal with bandwidth W and slowly sweep over the communications band in order to force the antenna off track. Equation (2) gives the signal-to-noise ratio for the link and from this the required received jammer power is

$$P_{JR} = WE_b = W/R \, \eta \, \frac{P_T A^2}{S^2 \lambda^2} \tag{10}$$

Since the crosslink is maintained with narrow beam antennas, the jammer will, in general, be located in the sidelobe coverage of the link antenna. The sidelobe levels fall off as a function of angle with respect to the main beam fairly rapidly for the phased array and more rapidly for the parabolic antenna. In theory, these levels will diminish without limit but in practice there is usually a "floor" level below which the average sidelobe level does not fall. This is largely due to things like parabola surface and shape anomalies, currents

induced on support structures, moding effects in the horn apertures, etc. A good rule of thumb for a well designed antenna but one which is not specifically designed for low sidelobes is that this floor is at about -10 dBi. The link equation for the jammer to satellite in the sidelobe region is then

$$P_{JR} = P_{JT} \frac{G_{JT}(.1)\lambda^2}{(4\pi S_j)^2} L \tag{11}$$

where P_{JT} is the jammer transmitter power, G_{JT} is the gain of the jammer transmitting antenna, S_j is the distance between the jammer and the satellite, and L is the attenuation over that distance. Substituting this into (10) and solving for $P_{JT}\ G_{JT}$, the required jammer EIRP, results in

$$P_{JT}G_{JT} = \frac{W}{R}\eta \frac{P_T A^2}{S^2\lambda^2} \frac{(4\pi\ S_J)^2}{.1\lambda^2 L}$$

$$= 160\ \pi^2 \frac{W}{R}\eta \frac{P_T A^2}{L\lambda^4} \frac{S_J^2}{S^2} \tag{12}$$

Using (12), some jammer requirements can be determined for variously located jammers. For earth located jammers, either surface based or airborne, Figure 7 is of interest. This shows the atmospheric absorption at three altitudes in dB/Km. Considering first, a surface based jammer, the attenuation through the total atmosphere in the zenith direction is about 145 dB at frequencies between the oxygen resonance lines shown in Figure 7 and over 200 dB at frequencies which coincide with the lines. In order to overcome this loss, for example, with a jammer located directly below one of the satellites using a +70 dBi gain antenna and a tracking receiver bandwidth as narrow as 1 Hz, a jammer transmitter capable of 10^{12} watts would be required to jam a crosslink designed in accordance with Figure 5. The jammer power required is substantially independent of the link data rate. The attenuation through the atmosphere decreases rapidly with altitude and at 50,000 ft. the attenuation (again between the resonance lines) is about 30 dB. An airborne jammer with a 50 dBi gain antenna

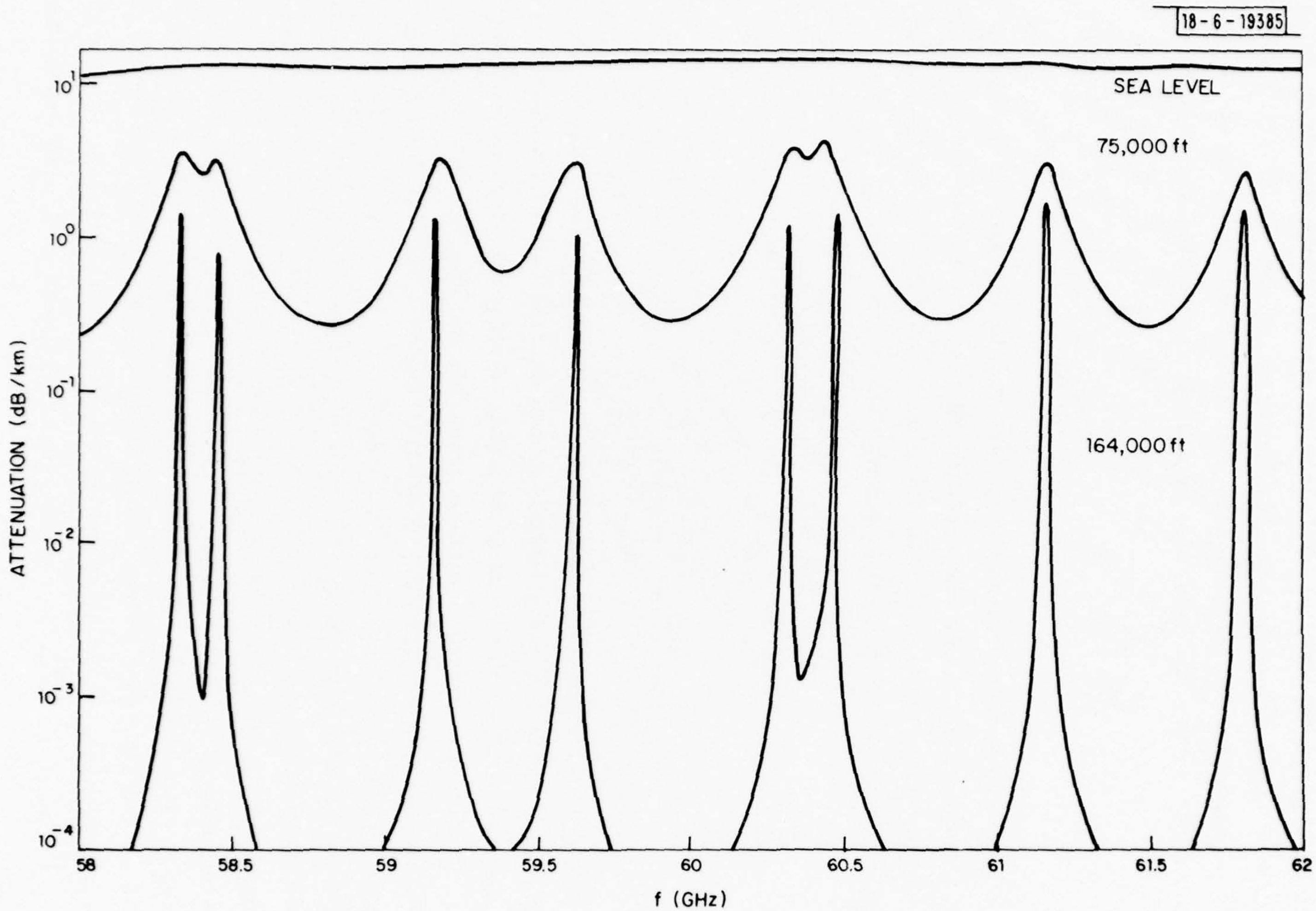


Fig. 7. Atmospheric attenuation at three altitudes.

(48 in. dia parabola) would require a spectral power density of 300 watts/Hz of tracking receiver bandwidth. Thus, if the tracking receiver bandwidth were 100 Hz, an adversary would need to fly a 48 in. parabola with a 30 kW transmitter at 50,000 ft. to disrupt the link. These computations lead to the conclusion that a 60 GHz crosslink is immune to earth-based jammers.

A space-based jammer in subsynchronous orbit, say 400 miles, will experience virtually no atmospheric attenuation. This reduces the transmitter power with the same 50 dBi antenna to .3 watts/Hz. This is feasible for a tracking receiver with a small bandwidth, i.e., 10-100 Hz. Tracking receivers using bandwidths of a kilohertz or more, however, would necessitate spaceborne jammers with transmitter powers in excess of 300 w. A jammer in synchronous orbit at, say, a range of 2,300 miles, again with a 50 dBi antenna would require 3 mw/Hz to disrupt the link. A crosslink which utilizes the full communications bandwidth for tracking and operates at data rates of 10^6 bps or more will require the jammer to generate, under these circumstances, 300 w or more power.

The foregoing leads to the conclusion that, in general, crosslinks in the 60 GHz region with bandwidths on the order of 1 MHz and tracking bandwidths of the same size are not likely to be considered jammable by an adversary. This conclusion, of course, applies to the more general case which places the jammer well away from the main beam. The link antenna sidelobes are much higher in gain than -10 dBi close to the main beam; and if an adversary can place a jammer in this area, the power required for effective jamming is much lower. For example, the jammer in subsynchronous orbit located approximately $2\frac{1}{2}$ beamwidths (on the second sidelobe) away from the mainbeam of the crosslink antenna will require only 4w of transmitter power to jam a 100 Kbps crosslink. This power level, however, assumes a +50 dBi gain antenna for the jammer. The beamwidth of the jammer antenna is then approximately .5°. This will probably require the jammer to actively track the communications satellite with an accuracy of about .1°. It is possible that this may not be feasible unless the jamming satellite is quite close to the satellite to be jammed.

IV. CONCLUSIONS

1. For data rates approximately less than 100 kbps, the phased array antenna provides a more desirable incremental launch weight than does the parabolic reflector antenna, provided the angular relationship between satellites in the link remains fixed within a few degrees. If the desired data rate is in excess of 100 kbps or the angular relationship between satellites is allowed to vary then the parabolic reflector antenna is the favored option. The minimum incremental launch weight of such a system depends on the assumed data rate. A typical value for a rate of 100 kbps is about 150 lbs.

2. The 60 GHz crosslink is relatively immune to jamming attack. The oxygen absorption of the earth's atmosphere makes jamming from surface based or air-borne jamming impractical. Spaceborne jammers are feasible with realizable antenna aperture sizes and transmitter power levels only on crosslinks which use relatively narrow (<100 KHz) bandwidths for communication, tracking or both. The exceptions to this latter conclusion are jammers which can be located within or very close to the mainbeam of the crosslink antenna.

APPENDIX I

DERIVATION OF OPTIMUM WEIGHT ALGORITHMS

The communications package is assumed to consist of three parts: those portions of the package with a total weight which is dependent on aperture size, those portions with a total weight which is dependent on transmitter power, and those portions with a total weight which is substantially independent of either the aperture size or the transmitter power. Thus, the weight of the package can be stated as:

$$W_c = W_1(d) + W_2(P_T) + W_o \qquad \text{(A1)}$$

The algorithm which reflects the weight of the communications package into the incremental launch weight is assumed to be of the form

$$\Delta W_L = K_1 W_c + K_2 P_B \qquad \text{(A2)}$$

where P_B is the buss power required to operate the communications package and K_1 and K_2 are empirically determined constants.

The buss power is also assumed to consist of a part dependent on aperture size, a part dependent on transmitter power, and a part independent of both. Hence,

$$P_B = P_1(d) + P_2(P_T) + P_o \qquad \text{(A3)}$$

Substituting (A1) and (A3) into (A2) yields

$$\Delta W_L = K_1[W_1(d) + W_2(P_T) + W_o] + K_2[P_1(d) + P_2(P_T) + P_o] \qquad \text{(A4)}$$

for the incremental launch weight.

We then propose to find the minimum ΔW_L with respect to d and P_T subject to the restriction imposed in (2), i.e.,

$$E_b/N_o = \eta \frac{P_T A^2}{KTRS^2 \lambda^2} \tag{A5}$$

I. PHASED ARRAY

Table A1 categorizes the various components of the phased array communications package into each of the three aforementioned classes for power and weight. We will then analyze each of these components in sufficient detail to describe the functions, W_1, W_2, P_1 and P_2.

A. Antenna Weight

Each antenna element is assumed to be a horn as shown

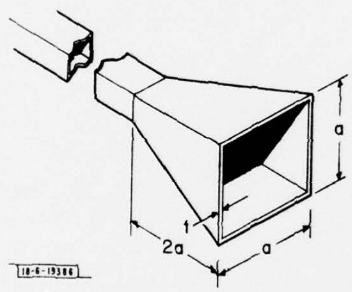


Fig. A1. Horn antenna.

in Figure A1. The horn aperture dimension is a, the length of the flare is 2a, and the wall thickness is t. The density of the horn material is δ. The weight of the horn is given approximately by

$$\begin{aligned} w_h &= 4\delta \cdot 1/2(a)\ (2a)\ (t) \\ &= 4\delta\ a^2 t \end{aligned}$$

For an array of aperture size d, there are d^2/a^2 horns. The total weight of the array of horns is

$$W_A = \frac{d^2}{a^2} \cdot 4\ \delta a^2 t = 4\delta d^2 t \tag{A6}$$

TABLE A1

PHASED ARRAY COMPONENTS

Component	Weight Dependency			Power Dependency			
	Aperture Size	Transmitter Power	None	Aperture Size	Transmitter Power	None	Requires No Power
Horn Array	X						X
Polarizer/ϕShifter/ ϕShifter Driver	X			X			
Corporate Feed	X						X
Diplexer			X				X
Transmitter PA		X			X		
Transmitter LO			X			X	
Transmitter Mixer			X			X	
Receiver Mixer			X			X	
Receiver LO			X			X	
Tracking Receiver			X			X	
Interconnecting Wiring			X			X	

B. Polarizer/ϕShifter/ϕShifter Driver Weight

There does not seem to be any necessity for a polarizer in a crosslink. Since the satellites are assumed to be attitude stabilized, the two antennas in the link have a fixed rotational relationship. In addition, the propagation medium does not distort the polarization of the transmitted wave. Linear polarization (which might be rotated by ground command), under these circumstances, is an attractive possibility. We include the polarizer in the computation on the chance that additional requirements not considered in this discussion may require its use. The polarizer (if used), phase shifter and phase shifter driver are paired with the individual horns in the array. Denoting the sum of the weights of each of these three components as w_p, the total weight for the array is

$$W_p = Nw_p \simeq \left(\frac{d\alpha}{60\lambda}\right)^2 w_p, \tag{A7}$$

using the relationship between the number of horns in the array and the scan angle capability, α, given in (5).

C. Corporate Feed Weight

The corporate feed structure is assumed to be binomial as shown in Figure A2. The feed structure as shown in the figure is assumed to be waveguide. For equally spaced horns, the weight of the structure can be expressed as the sum of the lengths, ℓ_1, plus the sum of the lengths, ℓ_2, and multiples of ℓ_2 times the weight per unit length of the waveguide. The sum of the lengths, ℓ_1 over the N elements of the square array is

$$\sum_N \ell_1 = (\sqrt{N} + \sqrt{N}/2 + \sqrt{N}/4 + \ldots)\ \sqrt{N} + \sqrt{N} + \sqrt{N}/2 + \sqrt{N}/4 + \ldots$$

which we approximate by the limit

$$\lim \sum_N \ell_1 = \sqrt{N}\ (\sqrt{N} + 1)$$

$$\simeq \frac{d\alpha}{60\lambda}\left(\frac{d\alpha}{60\lambda} + 1\right)$$

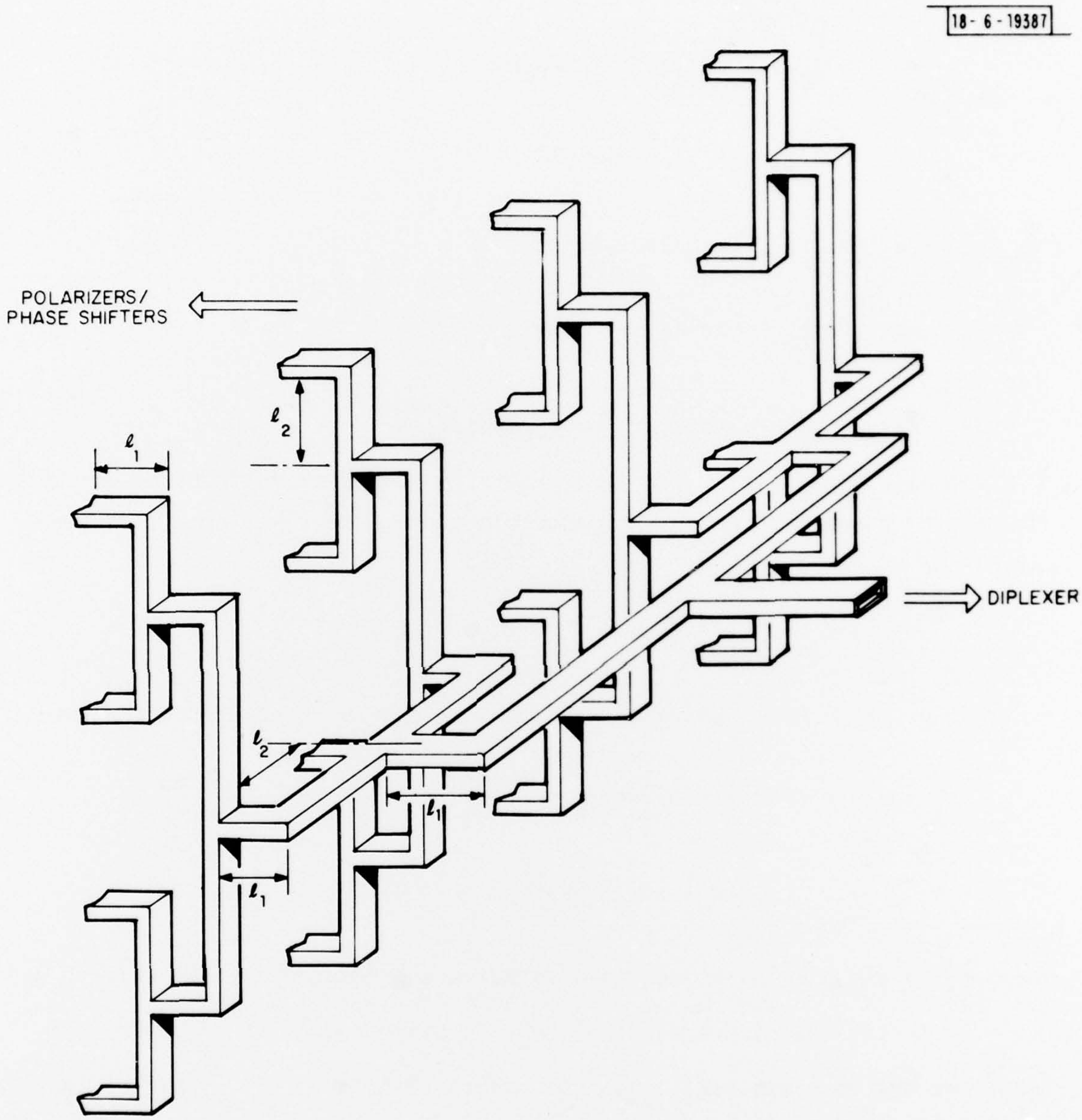


Fig. A2. 16-Element corporate feed network

The sum of the lengths, ℓ_2, can be written as

$$\sum_N \ell_2 = (\frac{d}{2} \log_2 \sqrt{N}) \sqrt{N} + \frac{d}{2} \log_2 N$$

$$\simeq (\frac{d\alpha}{60\lambda} + 1) \frac{d}{2} \log_2 \frac{d\alpha}{60\lambda} .$$

The weight of the feed network is then

$$W_F \simeq \sigma (\frac{d\alpha}{60\lambda} + 1) (\frac{d\alpha}{60\lambda} + \frac{d}{2} \log_2 \frac{d\alpha}{60\lambda}) \tag{A8}$$

D. Weight of Transmitter Power Amplifiers

The power amplifier weight can generally be expressed in terms of pounds per watt of power. Using this type of algorithm, the power amplifier total weight can be expressed as

$$W_{PA} \simeq w_{pa} P_T \tag{A9}$$

Using (A6), (A7), (A8) and (A9), we then can substitute into (A4) and

$$\Delta W_L \simeq K_1 [4\delta d^2 t + (\frac{d\alpha}{60\lambda})^2 w_p + \sigma(\frac{d\alpha}{60\lambda} + 1) (\frac{d\alpha}{60\lambda} + \frac{d}{2} \log_2 \frac{d\alpha}{60\lambda})$$

$$+ w_{pa} P_T + W_o] + K_2 [(\frac{d\alpha}{60\lambda})^2 p_\phi + \beta P_T + P_o] \tag{A10}$$

where p_ϕ is the buss power required to drive an individual phase shifter and

β is the buss power required to generate one watt of rf power.

(A10) can now be minimized subject to the restriction, (A5). Writing (A5) and noting that $A^2 = d^4$ for a square aperture

$$F(d, P_T) = \eta \frac{P_T d^4}{KTR \frac{E_b}{N_o} S^2 \lambda^2} - 1 = 0$$

Then

$$\frac{\partial \Delta W_L}{\partial d} + C \frac{\partial F}{\partial d} = 0$$

$$\frac{\partial \Delta W_L}{\partial P_T} + C \frac{\partial F}{\partial P_T} = 0$$

where C is a Lagrange multiplier. Performing the indicated differentiation results in

$$K_1 [8\delta dt + 2d(\frac{\alpha}{60\lambda})^2 (w_p + \frac{K_2}{K_1} p_\phi + \sigma) + \sigma (\frac{d\alpha}{60\lambda} + \frac{1}{2}) \log_2 \frac{d\alpha}{60\lambda} + \frac{\sigma}{2\ln 2} (\frac{d\alpha}{60\lambda} + 1)$$

$$+ \frac{\alpha\sigma}{60\lambda}] + 4C\eta \frac{P_T d^3}{KTR \frac{E_b}{N_o} S^2 \lambda^2} = 0 \tag{A11}$$

and

$$K_1 w_{pa} + K_2 \beta + C\eta \frac{d^4}{KTR \frac{E_b}{N_o} S^2 \lambda^2} = 0 \tag{A12}$$

Adding these two equations and noting that

$$\eta \frac{P_T d^4}{KTR \frac{E_b}{N_o} S^2 \lambda^2} = 1$$

produces

$$C = -\frac{1}{5} \{\Delta W_L + K_1 [4\delta d^2 t + (\frac{d\alpha}{60\lambda})^2 (w_p + \sigma) + \frac{\sigma d}{2} (\frac{d\alpha}{60\lambda}) \log_2 \frac{d\alpha}{60\lambda}$$

$$+ \frac{\sigma d}{2\ln 2} (\frac{d\alpha}{60\lambda} + 1) - W_o] + K_2 [(\frac{d\alpha}{60\lambda})^2 p_\phi - P_o]\} \tag{A13}$$

Substituting into (A11) and (A12) and solving for ΔW_L and P_T produces

$$\Delta W_{L_{min}} \simeq K_1 \{6\delta d^2 t + \frac{3}{2} (\frac{d\alpha}{60\lambda})^2 (w_p+\sigma) + \frac{\sigma}{12} [\frac{d\alpha}{60\lambda}(10 + 6 \log_2 \frac{d\alpha}{60\lambda})$$

$$+ \frac{d}{\ln 2} (\frac{d\alpha}{60\lambda} + 1) + 5d \log_2 \frac{d\alpha}{60\lambda}] + W_o\} \tag{A14}$$

$$+ K_2[\frac{3}{2} (\frac{\alpha d}{60\lambda})^2 P_\phi + P_o]$$

$$P_T \simeq \frac{\Delta W_{L_{min}} + K_1[4\delta d^2 t + (\frac{d\alpha}{60\lambda})^2 (w_p+\sigma) + \frac{\sigma d}{2} (\frac{d\alpha}{60\lambda} \log_2 \frac{d\alpha}{60\lambda} + \frac{1}{\ln 2} (\frac{d\alpha}{60\lambda}) + \frac{1}{\ln 2}) - W_o]}{5(K_1 w_{pa} + K_2\beta)}$$

$$+ \frac{K_2[(\frac{d\alpha}{60\lambda})^2 - P_o]}{5(K_1 w_{pa} + K_2\beta)} \tag{A15}$$

as indicated in equations (6) and (8).

II. PARABOLIC REFLECTOR

Table A2 categorizes the various components of the parabolic reflector communications package into dependency classes for power and weight. Figure A3 illustrates the concept of the antenna utilized in the derivation of the optimum weight algorithm.

A. Reflector Weight

The reflector is assumed to be a paraboloid of revolution and has a weight given by

$$W_R = \delta \frac{\pi d^2}{6} [\frac{(K^2+1)^{3/2}}{K} - K^2] \tag{A16}$$

where
- d is the diameter of the reflector
- K is the ratio of the focal length to the diameter
- δ is the weight per unit area of the material used in the reflector.

TABLE A2

PARABOLIC REFLECTOR ANTENNA

Component	Weight Dependency			Power Dependency			
	Aperture Size	Transmitter Power	None	Aperture Size	Transmitter Power	None	Requires No Power
Parabolic Reflector	X						X
Feed/lobing Modulator			X			X	
Feed Support	X						X
Feed Waveguide	X						X
Gimbal			X				X
Rotary Joint			X				X
Scan Motor Package			X			X	
Diplexer			X				X
Transmitter PA		X			X		
Transmitter LO			X			X	
Mixer			X			X	
Receiver LO			X			X	
Tracking Receiver			X			X	

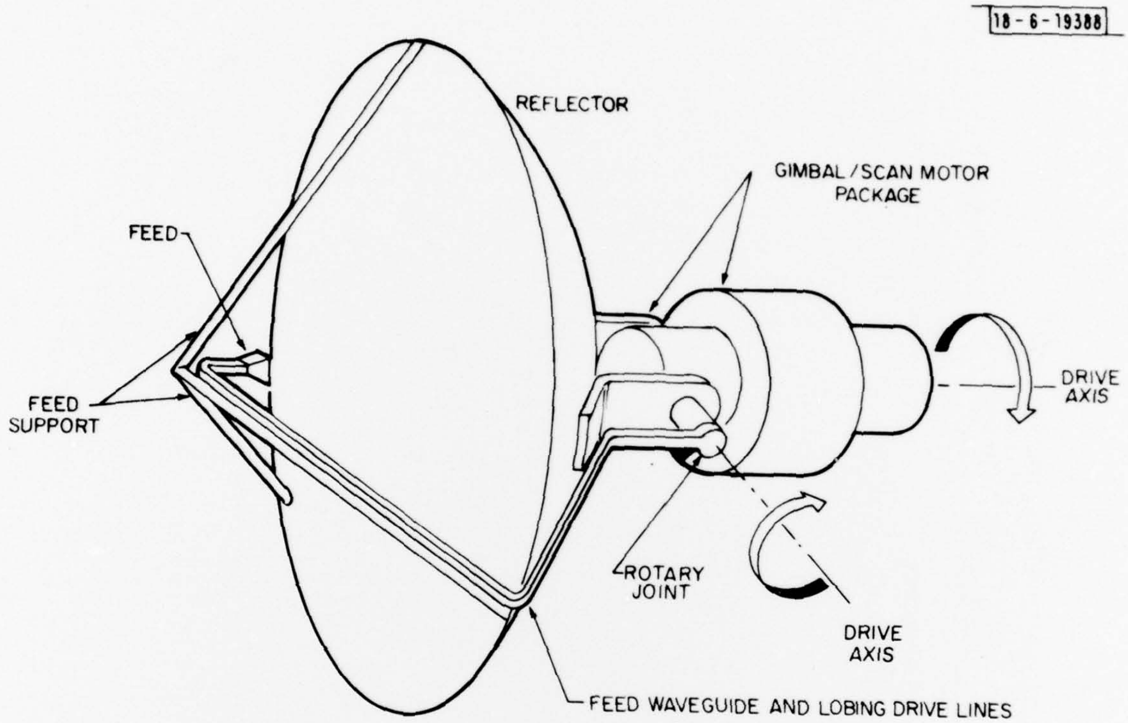


Fig. A3. Paraboloid reflector antenna.

B. Feed Support Weight

The feed supports are assumed to extend from the rim of the reflector to the focal point. If three supports are used, then their weight is

$$W_F = 3\gamma \frac{d}{4}\sqrt{\frac{8K-1}{K^2}} \tag{A17}$$

where γ is the weight per unit length of the strut.

C. Feed Waveguide Weight

Using Figure A3, the weight of the feed waveguide is given approximately by the weight per unit length of the waveguide times the length on a single support strut added to the radius of the reflector. This is

$$W_G = \sigma\left(\frac{d}{4}\sqrt{\frac{8K-1}{K^2}} + \frac{d}{2}\right) \tag{A18}$$

Using $W_{PA} \simeq w_{pa}P_T$ as the weight of the power amplifier and substituting into (A4) gives

$$\Delta W_L \simeq K_1\left\{\delta \frac{\pi d^2}{6}\left[\frac{(K^2+1)^{3/2}}{K} - K^2\right] + 3\gamma \frac{d}{4}\sqrt{\frac{8K-1}{K^2}} + \sigma\left(\frac{d}{4}\sqrt{\frac{8K-1}{K^2}} + \frac{d}{2}\right) + w_{pa}P_T + W_o\right\} + K_2\left[\beta P_T + P_o\right] \tag{A19}$$

where β is the buss power required to generate one watt of power.
(A19) can now be minimized subject to the restriction (A5).

Writing (A5) and noting that $A^2 = \frac{\pi^2 d^4}{16}$ for a circular aperture

$$F(d,P_T) = \eta \frac{\pi^2 P_T d^4}{16KTR \frac{E_b}{N_o} S^2 \lambda^2} - 1 = 0$$

Then $\frac{\partial \Delta W_L}{\partial d} + C\frac{\partial F}{\partial d} = 0$

$$\frac{\partial \Delta W_L}{\partial P_T} + C\,\frac{\partial F}{\partial P_T} = 0$$

where C is a Lagrange multiplier. Performing the indicated differentiation results in

$$K_1\ \{\delta\,\frac{2\pi d}{6}\,[\frac{(K^2+1)^{3/2}}{K} - K^2] + \frac{3\gamma}{4}\sqrt{\frac{8K-1}{K^2}} + \sigma\,(\frac{1}{4}\,\sqrt{\frac{8K-1}{K^2}} + \frac{1}{2})\}$$

$$+\ 4\ C\eta\ \frac{\pi^2 P_T d^3}{16KTR\,\frac{E_b}{N_o}\,S^2\lambda^2} = 0 \tag{A20}$$

and

$$K_1\ w_{pa} + K_2\beta + C\eta\ \frac{\pi^2 d^4}{16KTR\,\frac{E_b}{N_o}\,S^2\lambda^2} = 0 \tag{A21}$$

Adding these two and noting that

$$\eta\ \frac{\pi^2 P_T d^4}{16KTR\,\frac{E_b}{N_o}\,S^2\lambda^2} = 1$$

produces

$$C = -1/5\ \{\Delta W_L - K_1 W_o + K_1\delta\,\frac{\pi d^2}{6}\,[\frac{(K^2+1)^{3/2}}{K} - K^2] - K_2 P_o\}$$

Substituting into (A20) and (A21) and solving for ΔW_L and P_T produces

$$\Delta W_{L_{min}} \simeq K_1\ \{\delta\frac{\pi d^2}{4}\ [\frac{(K^2+1)^{3/2}}{K} - K^2] + 15\gamma\ \frac{d}{16}\sqrt{\frac{8K-1}{K^2}} + 5\sigma\ (\frac{d}{16}\sqrt{\frac{8K-1}{K^2}} + \frac{d}{8}) + W_o\} + K_2 P_o \tag{A22}$$

$$P_T \simeq \frac{\Delta W_L - K_1 W_o + K_1 \delta \frac{\pi d^2}{6} \left[\frac{(K^2+1)^{3/2}}{K} - K^2 \right] - K_2 P_o}{5(K_1 w_{pa} + K_2 \beta)} \tag{A23}$$

as indicated in equations (7) and (9).

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A brief study of the characteristics of a 60 GHz crosslink has been conducted. The study considers the incremental launch weight tradeoffs between a link using mechanically steerable parabolic reflector antennas and electronically steerable phased array antennas. An algorithm which determines the optimum compromise between transmitter power and aperture size for these two types of antennas is developed. It is concluded that the phased array antenna can be used only for small scan angles. With this restriction, the phased array antenna provides a better weight compromise for data rates below 100 kbps while the parabolic reflector antennas are to be preferred for data rates above 100 kbps.

The susceptibility of the link to jamming attack is also briefly studied. It is generally concluded that the link will be relatively immune to jamming attack provided that the autotrack function of the link and the communication function both operate over bandwidths of 100 kHz or more.

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